Inflation-deployed camera and hyper-thin mirrors

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ABSTRACT

Inflatable optics have the potential for a large reduction in launch mass and volume, but they involve significant challenges to achieve the wavefront accuracy required for diffraction-limited operation in the visible and near IR. Current studies identify two major subsets of this topic: 1) inflation-deployed structures with a monolithic, but rolled, hyper-thin primary mirror and 2) an inflatable structure and inflatable membrane primary mirror. We address the current state of the art, the challenges involved, and a program development plan.

Keywords: telescopes, space optics, adaptive optics, optical testing, hyper-thin mirrors, two-stage optics.

1. INTRODUCTION

Inflatable optics has a history of years of frustration. Some 20 years ago, the Defense Advanced Research Projects Agency (DARPA) began studying inflatable optics, but to maintain a stable surface, heavy defining rings were required. This canceled the goal of mass and volume reduction. The subject was revived by NASA with a new goal: compact, low-mass microwave antennas.

Within the framework of the new technologies of inflation-deployed space structures, we develop the rationale for ultralightweight, large-aperture camera systems. Optical system requirements are derived for an inflation-deployed camera, and the technology development needs in membrane mirrors, two-stage optics, and inflation-deployed structures and systems are described. This is a high-risk, very high payoff project whose specific implementation is strongly dependent on the success of a comprehensive technology development program. We are proceeding with a three-phase program: 1) Develop a 0.5-meter-class clear-aperture inflation-deployed camera testbed for hardware and software component technology development and deployment in a ground-based de-mountable vacuum testbed; 2) Develop a 2-meter-class clear-aperture camera system that is space qualified and ready for a flight testbed demonstration of the inflation-deployed camera; 3) Develop a several-meter-class clear-aperture camera system focused on achieving significant scientific measurement objectives for Earth, planetary, or astrophysics applications. Successful implementation of this program will enable cost savings of 10 to 100 times over conventional space optics systems and will enable the 25-meter-class space-optical systems previously thought to be impossible. Applications for the Planet Mapper mission, planetary orbiter mappers, and stretch technology for the Next Generation Space Telescope (NGST) and optical communications are discussed.

NASA deployed an inflatable, 14-meter microwave, parabolic dish from the Shuttle. A problem was that instabilities encountered in the inflation led to large amplitude oscillations. Nevertheless, the experiment was deemed to be a success inasmuch as the cause of the instabilities was ascertained and fixes were developed. In view of these problems, we believe it is desirable to examine the matrix of problems and possible solutions that could lead to large inflatable optics that can be used in the visible and infrared with evolving solid-state arrays. Some experiments with 1-meter-class inflatable mirrors by l'Garde resulted in surface-error maps in which the difference between the inflated mirror and a paraboloid showed a characteristic W-shaped error. No experiment resulted in a near-parabolic inflated mirror. This W-shaped error has remained a challenge and has led to skepticism concerning the future prospects for inflated parabolic mirrors of high accuracy.

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2. RATIONALE

Figure 1 shows the parametric relationship of mass to aperture diameter for various classes of telescope. The baseline points for folded telescopes and inflatable telescopes are from previous engineering concept studies by Meinel, Meinel, and Breckinridge.[1] The open areas represent the mass of the optical telescope and associated focal plane instrumentation. The shaded areas represent the remainder of the spacecraft system mass. In the absence of studies of space systems of various sizes, the slope of their boxes is uncertain. The general trend of the mass increasing according to the second power of size, however, seems to be reasonable. As a consequence, the slope of the boxes is taken from the size/mass scaling relationship of existing terrestrial telescopes.

It is obvious from Fig. 1 that the extremely low mass of the inflatable telescope is a strong driver toward a correspondingly small mass for the associated spacecraft. In our study, we have assumed that a low moment of inertia is made possible by the small moment of inertia of the inflated telescope. The related power requirement for management of the spacecraft is, then, correspondingly small, and thus the mass of the solar panels is small.

The net result cascading from the very low mass of the inflatable telescope is a very small total mass compared to even the low mass per telescope diameter for folded configurations like the folded astronomical space telescope (FAST).[1]
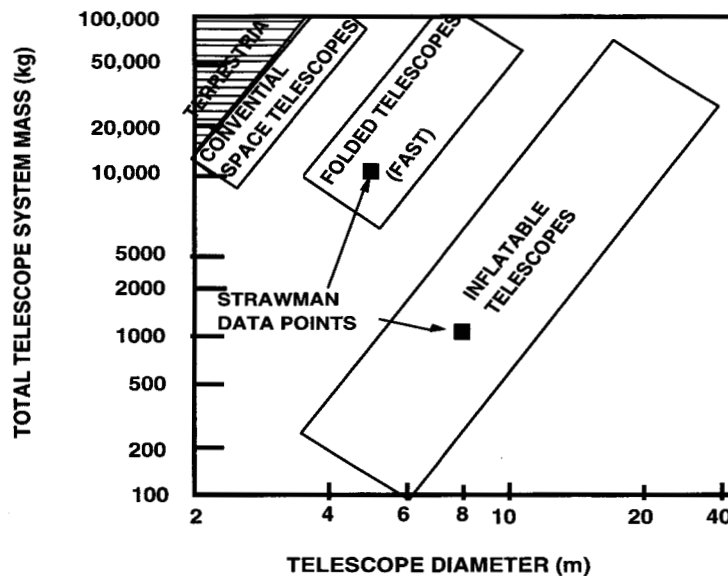
Fig. 1. Parametric relationship of total system kg mass vs aperture diameter for inflatable telescopes relative to terrestrial, conventional space telescopes and FAST. The two data points refer to strawman concepts for both folded and inflatable telescopes.

3. CURRENT STATUS OF EXPERIMENTS

We have re-examined the l'Garde data for uniform-thickness, monolithic thin films and find a simple explanation for the W-curve. A toy balloon naturally tends to form a spherical surface, as one can readily observe. An inflated-mirror membrane supported on a rigid planar ring also should tend to form a spherical surface. If you measure the sag-versus-aperture zone, and then match the nearest paraboloid to that sag data, there will be a residual sag. An opticist will immediately note the similarity of this residual to the sag curve for a Schmidt plate: the W-curve. In addition, the l'Garde data had an asymmetry in depth of the W-curve as shown in Fig. 2. This asymmetry can immediately be identified as coma, coma resulting from a
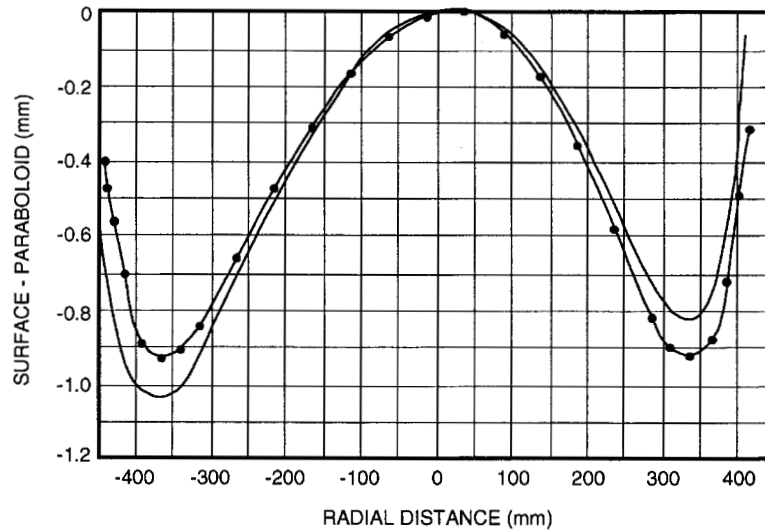
Fig. 2. Measured difference between a 6-mm membrane and the nearest paraboloid (solid curve) after correction for metrology system tilt (dots).

slight de-centering or tilt of the inflated surface from the assumed orientation of the parabolic curve. The most probable source of the observed asymmetry is a 3-arc-minute tilt of the inflated-mirror defining ring with respect to the plane of the metrology system used to measure the sag curve. After correction that makes the depths of the curve equal, there remains an asymmetry with respect to the central vertex of the curve. One would expect a membrane to inflate into a spherical surface, like a child's balloon. Unfortunately, when the edge is defined by a rigid ring, the actual surface is not a spherical surface, but an aspheric one, and one distorted in the opposite direction from the difference between a sphere and a paraboloid.

The obvious answer to the challenge of an inflatable mirror is to accept the surface that naturally results—and not insist on obtaining an aspheric or parabolic mirror. Opticists know of good optical designs that start with a spherical or near-spherical primary. No designs have been explored to date starting with an aspheric surface in which the edge is turned up relative to a sphere. Supposing that such a design can be achieved, then the small deviations in the surface shown in the l'Garde experiments require an improvement of the order of 500 times in the balance of the optical system to yield acceptable performance in the visible. This is a challenge for upgrading a wavefront in a minified exit pupil, discussed below.

4. CHALLENGES

In the quest for inflatable optical cameras, let us start with the most difficult options and then back off to a more realizable near-term goal. We assume that the major problems will be encountered with the large primary mirror, since smaller optics will not necessarily be inflatable optics.

After accepting the spherical surface that can be obtained, there are still many specific challenges to be met in order to achieve high-acuity inflatable mirrors. Let us look at each of the following:

1. Obtaining the design curvature

2. Maintaining intrinsic accuracy

3. Upgrading to visible passband requirements

4. Collimation with respect to other smaller optics in the system

5. Packaging a curved membrane into a flat-folded package

6. Effect of folding and stretching a reflective membrane

7. Lifetime on orbit

8. Adaptive upgrading

4.1 Obtaining the design curvature

Placing a flat elastic membrane under pressure will result in an approximately spherical surface whose curvature is a function of the pressure. Similarly a pre-formed curved non-elastic but flexible membrane can be tensioned to reproduce the pre-formed curvature by means of an applied pressure. In both cases the resulting surface will not have sufficient accuracy for high acuity applications resulting from zonal surface errors as well as absolute curvature error.

4.2 Maintaining intrinsic accuracy

Stability of the intrinsic accuracy of the inflatable primary mirror is essential, although, in principle, upgrading via adaptive correction is possible. If maintaining pressure is required, the probability of loss of pressure is a concern. This problem would be eased if a UV-polymerizable membrane were available, but serious lifetime issues are involved. The best near-term option is to use a flexible, but non-elastic, hyper-thin mirror. Such a mirror could not be folded, but could be rolled into a cigar-shaped cylinder. A parabolic surface can be rolled, since any cut through a paraboloid is an identical parabolic curve. We will return to this option later.

4.3 Upgrading to visible passband requirements

Upgrading a stable surface was explored during the development of concepts for the 20-m Large Deployable Reflector,[2] a Great Observatories candidate when that class of space observatories was ended. The concept was named "Two-Stage Optics." In this, the wavefront correction is applied, not to the primary mirror itself, but to a much smaller optical surface located at an image of the primary mirror—an exit pupil. Computer modeling showed that large errors could be significantly reduced in this manner. Perhaps the most dramatic application of this concept was in correcting the flawed Hubble Space Telescope (HST). The Jet Propulsion Laboratory Wide-Field and Planetary Camera 2 (JPL WF/PC-2) has a pupil close to the 1-cm diameter secondary mirror where the correction for the HST primary mirror error was successfully placed.[3]

Meinel and Meinel[4] showed that the correction factor was related to the ratio of the primary mirror diameter to the exit pupil diameter. This means that the stable errors of an inflatable mirror can be corrected by a small element whose diameter is set by the required wavefront error (WFE) reduction factor. Depending on the exit pupil diameter, an improvement factor of 100 to 1000 times is a reasonable goal. This sets the absolute accuracy required for an inflatable mirror at a more likely achievable value.

4.4 Packaging a curved membrane into a flat-folded package

Folding a plane membrane mirror into a flat package is easy, but folding a pre-curved membrane into a flat package is impossible. Hence, "soft packaging" becomes the required art.

There is one particular pre-curved shape that can be rolled into a compact cylinder: a paraboloid. If the mirror substrate is formed, for example, by spinning the polymer on a curved substrate during polymerization, the resulting hyper-thin mirror could be rolled. This is possible, since any cut through a paraboloid is an identical parabolic curve, and thus rolling involves no stretching of the membrane.

4.5 Effect of folding and stretching a reflective membrane

The optical effect of creases at the folds is to add in highly localized slope errors. These can be masked out in the exit pupil, so the severity of this issue is only the lateral extent of the resulting wavefront error. Stretching of the reflective membrane during inflation will also result in a loss of reflectance. We have observed that stretching a membrane results in its initially continuous reflective film breaking up into discrete islands, causing reflection degradation. This ensemble of reflective islands would also cause increased scattered light.

4.6 Lifetime on orbit

Supposing that all the above issues are solved, the final issue is the lifetime on orbit of a mirror and structure consisting of thin inflatable films. One answer is to reserve these low-mass, compact pre-launch optics for short lifetime missions where the goal is the lowest possible payload mass and launch vehicle size.

4.7 Adaptive upgrading

The optical performance of the deployed camera can, in principle, be further upgraded. This would require addition of wavefront error sensor(s) and an adaptive optical element at an exit pupil.

5. EXAMPLE CONFIGURATIONS

We have prepared two example configurations: 1) a fully inflatable camera and 2) one using a hyper-thin rolled primary mirror.
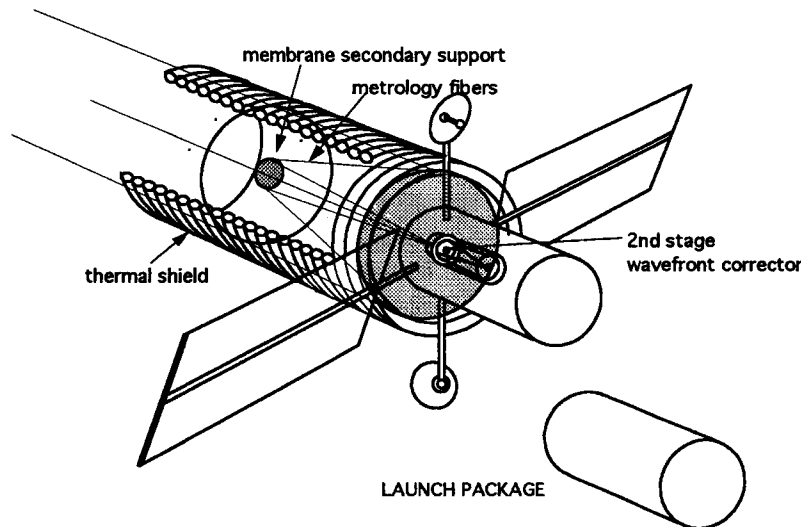
5.1 Fully inflatable camera

Fig. 3 shows a fully inflatable camera where the primary mirror and camera structure are all inflatable. A thin transparent window provides the enclosure to inflate the thin-film mirror.

The secondary and 2-stage optics module are standard rigid optics in rigid mounts. The support structure that holds the secondary mirror also provides a double-shell light and thermal shield for the camera. A carbon-fiber metrology truss is shown defining the position of the secondary mirror.

5.2 Hyper-thin rolled mirror camera

A cross section of the large inflation-deployed optics (LIDO) camera is shown in Fig. 4. The stowed rolled mirror is shown at left, with the deployed camera shown at right. After separation, the camera package is rotated 90° for the inflation deployment of the structure. The last step of the deployment is unrolling and locking the hyper-thin mirror.

Fig. 3. Schematic configuration for an inflatable camera in which the primary mirror is also an inflated membrane. The secondary mirror is mounted on the pressure containing membrane.

The three stages in deployment of a hyper-thin rolled primary mirror are shown in perspective in Fig. 5. The diameter of the primary is set by the length of the launch vehicle shroud. When the primary mirror is deployed, the cylindrical package is rotated 90°, and the inflatable structure is deployed. Six metrology arms are deployed to better define the unrolled curvature of the hyper-thin mirror. The rest of the structure is defined by means of a carbon-fiber metrology truss.
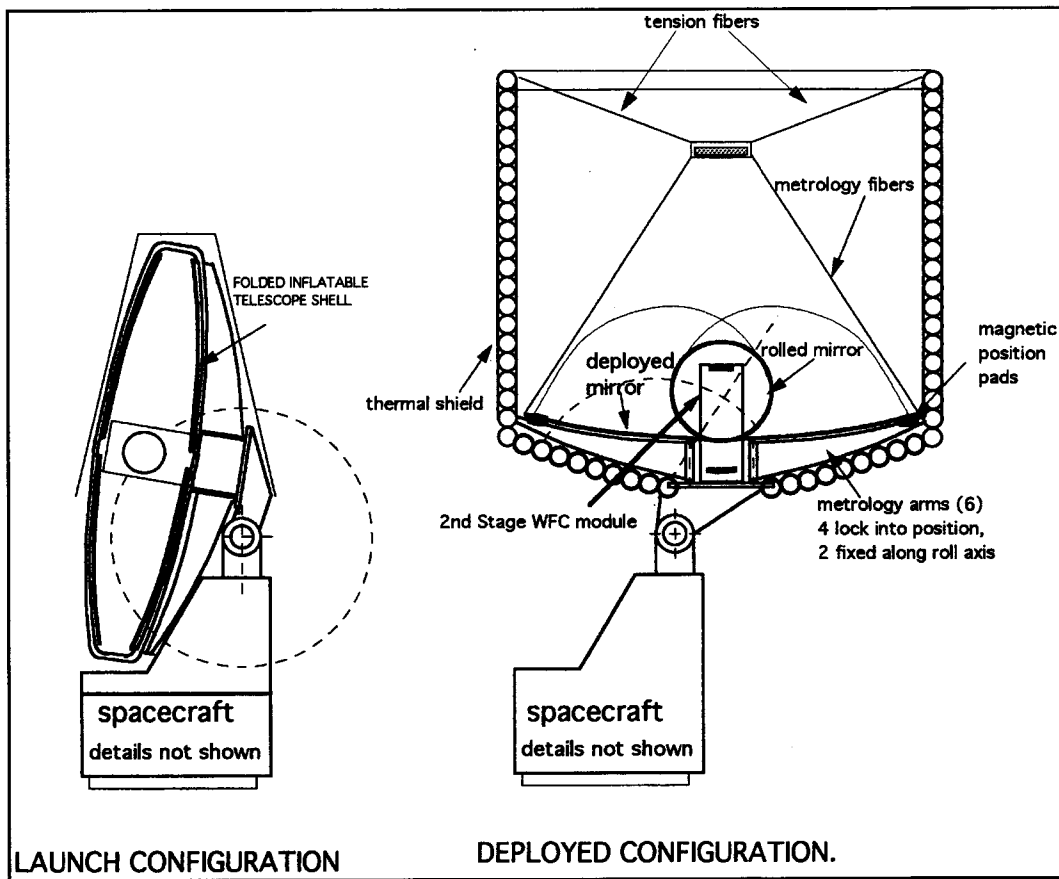
Fig. 4. Cross section of a rolled hyper-thin mirror in launch configuration (left) and positioned for inflation (right). Note that deployable metrology arms are provided to define the precision of deployment of the primary mirror.

6. PROGRAM PLAN

6.1 Develop a point design vision

Develop a point design vision for a space science telescope and a technology demonstration precursor. To do this, create an integrated system architecture, and establish

- Science measurement objectives
- An opto-mechanical design approach
- Ray-trace and tolerance for the telescope and two-stage optics
- Communication requirements
- Pointing stability

Include a detail design of a demountable sub-scale inflation-deployed ground testbed system with these draft requirements:

- A full telescope fore-optic and two-stage optics deployable assembly
- Packaging and precision deployment
- Implement candidate packaging and deployment scenarios
- Establish two-stage optics and wavefront sensing and control
- Implement candidate two-stage optics architectures
- For a membrane mirror, implement candidate membrane mirror materials and architectures

LIDO–SHROUD @ SEPARATION

LIDO–MIRROR UNROLLING

LIDO–DEPLOYMENT COMPLETED
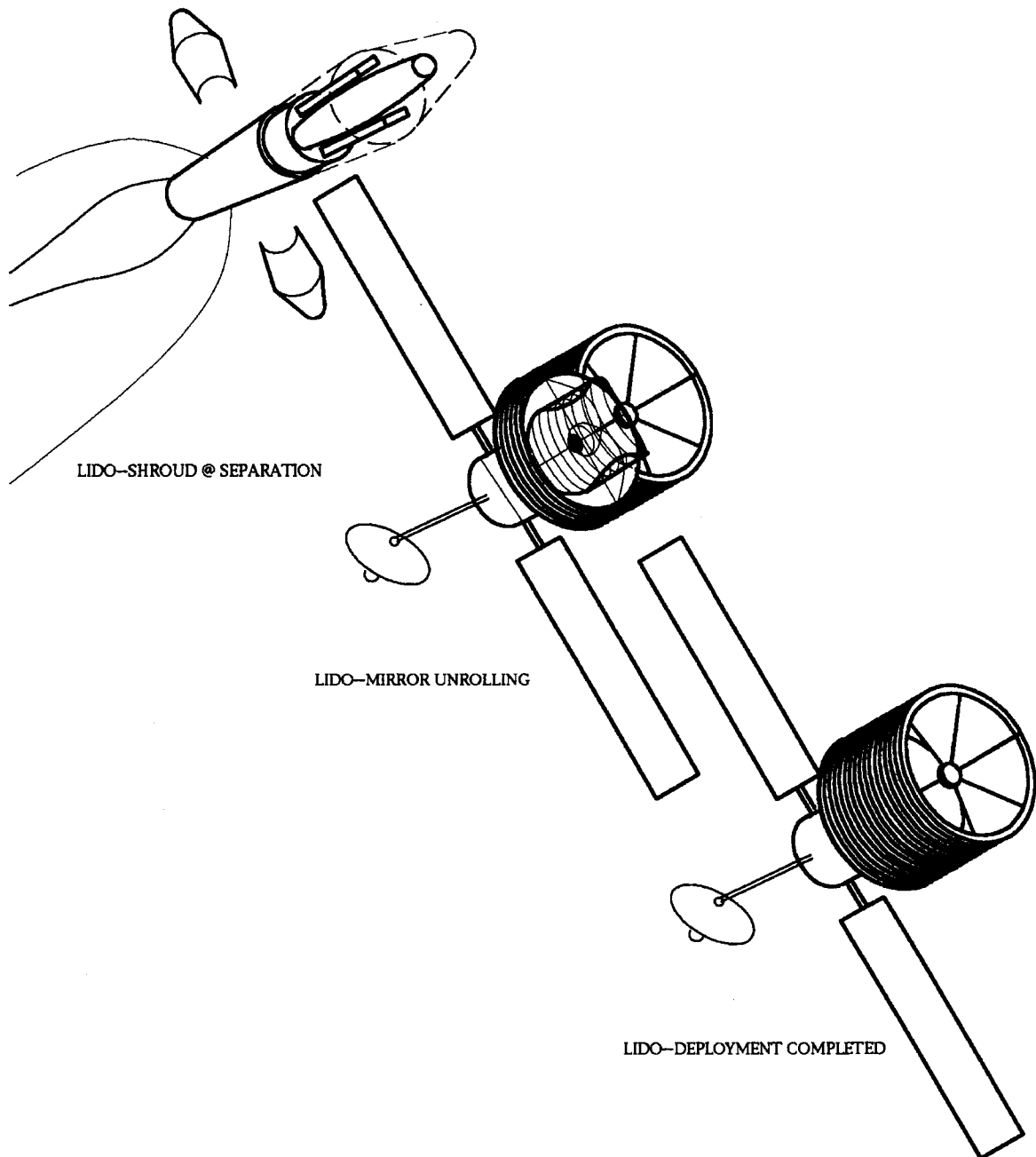
Fig. 5. Three stages in the deployment of an inflation-deployed camera in which a rolled hyper-thin mirror is used. The fiber metrology truss is also shown, defining the position of the secondary mirror relative to the primary mirror.

6.1 Develop a point design vision (contd)

A cost estimate for the program:

- A formal external review panel convened to assess the detail design of a demountable sub-scale inflation-deployed ground testbed system
- Technical community support through peer-reviewed papers in the open literature

6.2 The System Engineering Process

Identify and list technology development needs:

- Thermal, radiation, and meteorites environment
- Launch vehicle
- Packaging and precision deployment architecture
- Materials
- Structures
- Mechanisms
- Communications
- Rigidization of materials
- Reflectivity and scattered light
- Optical contamination
- Temporal and dimensional stability
- Adaptive structures & control
- Robotics and automation
- Flight science architecture
- Technology flight demonstration

Modify the point concept designs as needed. Create a brief roadmap for each of the most critical technologies. Also, identify cost, schedule, and performance, and prepare a preliminary plan.

6.3 A Request for Proposal to industry

Prepare and issue a Request for Proposal (RFP) to industry for the technology development_program and for participation in the flight test technology demonstration unit. Prepare a cost estimate for the program.

6.4 A roadmap

Create a detailed technology development roadmap with cost, schedule, and performance parameters. Understand the scalability of the smaller testbed to the larger ultimate space-science optical system. Prepare a cost estimate for the program.

7. CONCLUSIONS

It is our opinion that experiments leading toward inflatable and inflation-deployed cameras of very low mass and pre-launch volume are warranted with the goal of achieving low-cost/fast space missions for specific science objectives of the 21st century.

8. ACKNOWLEDGMENTS

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